

Landslide disaster in the loess area of China

ZHOU Jin-xing¹, ZHU Chun-yun², ZHENG Jing-ming³, WANG Xiao-hui¹, LIU Zhou-hong⁴

(¹Chinese Academy of Forestry, Beijing 100029, P. R. China)

(²Qinghai Forestry Research Institute, Xining 810016, P. R. China)

(³Beijing Forestry University, Beijing 100083, P. R. China)

(⁴China Children and Teenagers' Fund, Beijing 100000, P. R. China)

Abstract: China is the country with most widely distributed loess area in the world, and its loess area accounts of 6.63% of total nation land area. The landslide disaster occurs frequently for complex natural condition and becomes major factors hindering the social and economic development of loess regions. Through different indexes, the authors divided the landslides into 9 principal types and analyzed the distribution characteristics of loess landslide in time and space, the affecting factors and mechanism of landslides. It is pointed out that time and spatial distributions of landslides are closely correlative to topographic and geomorphic conditions, earthquake and rainfall, and the key influencing factors include topography, geomorphology, new tectonic movements, earthquake activity, surface water, ground water and human activities. The authors emphasized that the natural condition of loess areas was favorable to landslides, human activities impelled its occurrence and that controlling the loess landslide was an urgent task for sustainable development in the loess zone.

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General situation

China has an area of 655.3 thousand km² of loess area, accounting for 6.63% of its total land area. Continuous loess area in the Loess Plateau (Hu 1988, Wen 1994) is 440 thousand km², consisting of eastern Qinghai Province, eastern and middle Gansu Province, southern Ningxia Province, northern and middle Shaanxi Province, western Shanxi Province, and western Henan Province. The other scatters in Xinjiang Province, Northeast, Taihang Mountain, Shandong Province, and Nanjing City. Particularly, the Loess Plateau is famous for continuum, great development thickness, landform, relief and typical lithology composition.

Loess regions possess abundant resources of mineral, water, electricity, land, light, and heat and have huge development potential. However, the loess area has characteristic of loose loess lithology, large pore, developed vertical joint, and weak erosion resistance (Shan 1990). The chronical rising of the crust of the Loess Plateau leads to severely incised valley, fragmented topography, criss-crossed gully and steep slope. Therefore, geological environment is highly frail in loess area. The main loess area

belongs to arid and semi-arid areas with high intensity of average annual precipitation. Under the condition of nature, landslide and mud-rock flow happen frequently. In recent twenty years, population in loess regions increases so rapidly that it has reached 81.49 million, accounting for 7.8% of the nation's population, and its average annual increase rate (16.7%) in 1980 was higher than the nation's population increase rate (12.8%). With the rapid increase of population and the development of engineering economy construction, irrational human activities, such as excavating foothill, filling hillsides and over-cultivating, frequency and intensity of natural disasters are further accelerated. Compared with other areas in China, the industry of loess area develops slowly; agriculture is in a low state, which leads people to a relatively poor life. In 1985, the total output value of industry and agriculture was 809.04 hundred million yuan, accounting for 6% of that of the nation, averagely increasing by 10% as against that in 1980, lower than 12% of increase rate of the nation. Frequent natural disasters are major factors hindering the social and economic development of loess area (Liu 1989).

According to statistics, one third of landslide disasters occurred in loess area. From 1949 to 1990, at least 1025 people directly died from landslide disasters merely in the part area of the three provinces of Shaanxi, Gansu, and Qinai. On August 8, 1955, loess landslide occurred at Wolong Temple in Xibao Section of Longhai Railway Line damaged 230-m roadbed and suspended the transportation for several days. On March 7, 1983, loess landslide of Sale Mountain in Dongxiang County, Gansu Province in a moment resulted in three counties to be covered, 237 people

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Biography: ZHOU Jin-xing (1972-), male, Ph. D., associate professor in Chinese Academy of Forestry, Beijing 100029, P. R. China. E-mail: zjxqsy@rif.forestry.ac.cn

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animals killed, and 1000-m roads, over 29-hm² farmland, and two reservoirs destroyed. On August 11, 1990, loess landslide occurred at lathe factory, Tianshui City, ruined six workshops and killed seven people. In addition, many famous large disasters such as Bailu Plateau Form Landslide, Haiyuan Earthquake Landslide, and Jiangliu Landslide happened in loess regions. Landslide caused tremendous economic losses to human beings due to its extensive distribution and high frequency. In 1995, landslides happened over 3000 times and resulted in at least 776 people died and direct economic loss of 23.52 hundred million yuan. In the 1990s, extremely active loess landslide threatened people's life. It is urgent that loess landslide mechanism, forecast, and disaster reduction measure should be studied so as to promote sustainable development of ecological environment in loess area (Zhao *et al.* 1995; Li 1989)

Principal types of loess landslide

According to research results (Du 1984; Lu 1984), the principal types of loess landslides were divided into 9 types: 2 types based on landslide material, 5 types based on development position of landslide surface, and 2 types based on mechanism of landslide movement (Table 1).

Table 1. Principal types of loess landslide

Classified indicator	Types of landslide
Landslide material	Loess landslide
	Loess-laterite layer landslide
Development position of landslide surface	Loess landslide
	Loess-laterite joint layer landslide
	Loess-laterite layer horizontal landslide
	Loess-laterite layer tangential landslide
Landslide movement	Loess-nonlaterite joint layer landslide
	Slow gliding landslide
Mechanism	Collapsing-gliding landslide

It is recorded that loess landslide accounts for over 70% in the Loess Plateau, while loess-laterite layer landslide accounts for less than 30%. The latter is mostly huge, more than one million m³. It is counted that the proportions of loess landslides, loess-laterite joint layer landslide laterite, loess-laterite layer horizontal landslidelaterite, loess-laterite layer tangential landslidelaterite and loess-nonlaterite joint layer landslidelaterite in loess area are 40%, 30%, less than 5%, 20%, and less than 10%, respectively. Slow gliding landslide glides slowly. During the gliding period, it is gradually disassembled or glided slowly in a whole. Most of these landslides are various old landslides. The minority is loess landslides or loess-laterite joint layer landslideslaterite. Collapsing-gliding landslide glides rapidly. This kind landslide scatters in loess area vastly, representing the majority of movement mechanisms of new loess landslide. Due to its rapid gliding, collapsing-gliding landslide often causes severe disasters. In

loess area, almost all catastrophic landslides with people died or injured and great property loess are collapsing-gliding landslides.

Distribution pattern

Landslides in loess area, affected by geological composition, stratum lithology, landform, climate and human activities, are distributed with apparent rules of time and space (Su *et al.* 1995; Zhang 1979).

Distribution rule in space

Landslides in loess area are distributed in a strip along plateau form, ridge, edge of loess hill, and bank of valley around the edge of tectonic basins of the Cenozoic Era and the Mesozoic Era. In addition, the landslides apparently affected by precipitation are abundant in areas with more than 400 mm of annual precipitation and sparse in the areas with less than 400 mm of annual precipitation (Li *et al.* 1998).

Due to a favorable landform, the landslides are exceedingly abundant around the edge of tectonic basins of the Cenozoic Era and the Mesozoic Era. From the edge of a basin to the center, landslide is distributed from dense to sparse. Especially in laterite layer basin of the Cenozoic Era, mudstone of the Tertiary Period is developed, easily intenerated when touching water. The particular binary composition consisting of upper loess and lower laterite layer is beneficial to landslide development. Therefore landslides around laterite basin of the Cenozoic Era in loess area, such as Huangshui-Linxia Basin, Longzhong Basin, Xiji Basin, Guanzhong Basin, and Shaanbei Basin, etc, are distributed densely. According to statistics, the number of landslides of more than 500 mm in width is over 10 per 100 km².

In the plateau form, ridge, loess hill, and riverside of loess area, landslide is developed due to favorable incised topography, such as Dongzhi Plateau Form, Luochuan Plateau Form, Bailu Plateau Form, surrounding ridge, edge of loess hill, small edge of plateau Form, and bank of Weihe River, Baxie River, Jing River and their branches. According to a survey, the number of landslides of more than 500 mm in width is over 5 per 100 km². In these zones, landslides are developed more densely in the terrane of the Tertiary Period.

In the loess plateau, there are 3 earthquake strips: north-south earthquake strip of Liupanshan Mountain in Yinchuan-Tianshui-Wudu line, west earthquake strip of Huxi, Jibei in Lanzhou-Tianshui line, and east earthquake strip of Hudong, Jibei in Weinan-Xi'an-Baoji line, which are all active earthquake strips in China. Famous Haiyuan earthquake of magnitude 8.5, Hua County earthquake of magnitude 8, Tongwei earthquake of magnitude 7.5 and Tianshui earthquake of magnitude 7.5 happened in these earthquake strips. Affected by earthquake, landslide is developed densely in earthquake strips. According to rele-

vant data, 6-magnitude earthquake can induce a large number of landslides in loess area.

Landslide occurs sparsely in the northern loess plateau with less than 400 mm of annual precipitation, but frequently in the other area with more than 400 mm of annual precipitation.

The joint of earthquake strips is dense developing area of landslide. It is investigated that all dense landslide areas are at joints of landslide prone sections, such as Tianshui, Xining-Linxia line, peripheral Baoji-Weihe line, peripheral Xi'an, peripheral Lanzhou, and peripheral Yan'an, among which Tianshui ranks first in the terms of landslide distribution and concentrated landslide area.

Tianshui is located in the eastern edge of the third laterite basin of Longzhong, and the middle reaches of Weihe River, the joint of Yinchuan-Tianshui-Wudu earthquake strip and Lanzhou-Tianshui earthquake strip. In this region, new tectonic movement and river downcutting are strong, landform is fragmented, binary composition of loess and laterite layer is developed, and annual precipitation is 580 mm with centralized precipitation and a large number of rainstorms. The landslide in this area amasses all characteristics of dense landslide area in loess area. Density of landslide distribution and characteristic of development and movement type are mostly typical in loess area. Density of landslides is over 20 per 100 km².

Distribution rule in time

Precipitation and the dynamic characteristics of earthquake affect the time of landslide development in loess area distinctly. About 90 percent of landslides in this area are related to precipitation and earthquake. Affected by dynamic characteristic of precipitation, landslides related to precipitation mostly happen in rainy season of July, August and September. The frequency of landslide corresponds with the active period of earthquake. Every more than 6-magnitude earthquake caused much more landslides. For example, during the periods of Tianshui earthquake of magnitude 7.5 in 1654, Tongwei earthquake of magnitude 7.5 in 1920 and Haiyuan earthquake of magnitude 8.5 in 1920, landslides occurred in all the earthquake areas mentioned.

In addition, landslide frequently occurs in an ice-melting period from March to May. Famous Saleshan landslide, New Saleshan landslide, and Wolongshi landslide all happened in this period.

Influencing factors and mechanism analysis

Topographic and geomorphic conditions

Topographic and geomorphic conditions are necessary to landslide development. Even if geologic structure and stratum lithology exist, landslide does not happen without topographic and geomorphic conditions of landslide occurrence (Editorial Groups of Landslide corpus 1984).

The fundamental characteristic of relief outline in China

is ladder-like, high in the west and low in the east. The surface can be divided into three levels. The loess plateau is located in the second step. The characteristic of relief in the loess plateau mainly consisting of plateau form, ridge, and edge of loess hill is as follows: first, many gullies and fragmentized ground; second, deeply incised gully, high difference in altitude and severe undulated topography; third, steep slope and large ground degree. According to incomplete statistics, the number of gullies of more than one kilometer long in loess area is about 30. The density of gully is small in the Gullied Loess Plateau Region, about 2.4-2.7 km/km², whereas it is larger in the Loess Gullied Hilly Region, about 3.5-8.05 km/km². There are 2-8 1-km-long gullies in one square kilometer area. That is, more than one forth, even a half land becomes gully. Because of severe erosion, gully is cut down to bedrock in many regions. The height difference is variational from the ridge to the foot of hill, and that in Gullied-hilly loess region is small, and the general range is between 10 m and 60 m. The largest range can reach 80-100 m. However, the height difference in Gullied-highlands loess region is obvious, the general range is between 40 m and 100 m, and the largest range can reach 150-200 m or more. So fragmented loess ground and strong undulating land provide favorable conditions for landslide occurrence (Li 1989).

Stratum lithology effects

Loess is soil accumulation of the Quaternary Period, and has a yellow or brown yellow surface, most of which contains several interlayer of red brown fossil soil. It has a characteristic for developed vertical joint, vulnerable drought crack, high holecoefficient and low moisture content, which provide favorable conditions for rainfall infiltration. Because of the loess characteristics of chemical component, granule composition, structure shape, permutation and combination, inteneration and settlement, when the loess meets water, its intensity is rapidly decreased and it is named hole-settlement loess. If the other conditions are provided, landslide may happen. Therefore loess stratum is a fundamental factor of landslide occurrence (Zhao *et al.* 1995; Li *et al.* 1998; Ma *et al.* 1998).

Red soil, mudstone, sandstone, and shale are extensive in lower loess stratum. With the characteristics of relatively loose lithology of these strata, low mechanical intensity and vulnerable inteneration; it is easily to form a landslide surface in loess area when meeting water.

New tectonic movements and earthquake activity

New tectonic movement plays a dominant role in the slope development. After the later Pleistocene Epoch of the Quaternary Period, the recent tectonics movement becomes strong, the mountain, upland and plateau are uplifted, and the river and valley are downward because of downcutting. All of these make the greater difference in altitude of slope continuously, and form high slope (Zhang 1979). Many valleys are developed along fissure, which

provide landslide development at topographic and geomorphic conditions. Faultage in slope section accelerated to landslide development because the existence of faultage promoted infiltration of the rainfall and surface runoff. Faultage surface may become rip surface and slip-page surface of landslide, and the activity of faultage impels creepage and distortion of slope.

Earthquake activity has close relation with landslide development. For example, Haiyuan earthquake, which happened in Ninxia, induced large-scale landslide.

Strong surface tremor caused by earthquake brings about the change of structure and intensity of slope body, makes rock soil loose or compact, even liquefies, and reduces the shear-resistance strength of slope rapidly. Earthquake force brings slope abrupt displacement. Therefore, earthquake makes not only slope in the state of creepage and distortion slip, but also slope in the stable state slip.

Water effect

Landslide occurrence has close relation with water effect (Lei 1995). Water effect on landslide is discussed in the three aspects, rainfall, surface water, and ground water (Ma.D & Zeng Kang 1998).

Rainfall effect

Vertical infiltration of rainfall and surface runoff along the fissure can make water content of hill land increase, even saturate. When a great deal of rainfall reaches confining layer to form phreatic water layer, the cohesive force of soil body and frictional force of interlayer greatly decrease, and is favorable to landslide occurrence.

Surface water

Because the hillside can be cut down and eroded continuously by the surface water including the mountain stream and the river, the hillside can become unstable and its slopes become steeper and steeper, the landslide can occur easily.

Ground water

The existence and change of ground water can directly affect gravitational condition of slope and mechanical characteristic of rock soil, which are main factors affecting slope stability.

It is observed that when water content of red soil increases to 35%, shear-resistance strength decreases by 60%. The decrease of shear-resistance strength of mud-stone or shale in saturation is 30-40% lower than that in natural state. If ground water converges into a layer on the top of confining layer, it will produce buoyancy acting on upper soil body, resulting in decreasing sliding-resistance force. Ground water dissolves diffuent material of rock soil, changes chemical components and structure of rock soil, and even forms latent erosion and corrosion. The rise of ground water level produces lenitic and dynamic pressure,

and then affects slope stability.

Human activity effect

With the development of social economy, people utilize and reform nature more and more widely. In industry, agriculture, transportation, mineral resources, irrigation works, and the exploitation of cities and counties, the problem of border slope is inevitably involved. In the respect of landslide, breakdown and mud-rock flow, human factors are playing an increasingly important role.

On the border of loess plateau form and valley slope of loess hill, flat ground is rare, building houses by leveling slopes are universal, and cave-houses are dig in steep slope formed by cutting slope in some places. All of these reduce supporting force of the bottom of the slope, and decrease the stability of the border slope. In the catastrophic landslides and breakdown happening in recent years, a majority of landslides are related to human cutting slopes.

Digging soil in the bottom of loess slope areas is a factor of landslides occurrence. In addition, vegetation has a function of protecting slope. In the 1950s, however, unwise deforestation brought about severe damage of mountain forest, particularly in low mountain area, the forest resources have been on the verge of extinction. Reclaiming lands brought about the damage of grasslands, resulting in landslide in reclaimed areas of higher slope.

As stated above, loess areas provide landslide formation with convenient conditions, such as favorable border slope, and infiltration of rainfall and surface runoff. Stratum lithology accelerates water conservation and rising ground water. Affected by ground water, fragile surface is formed. Soil produces shear-damage-surface along fragile surface with the action of gravity and external forces. The formation of sliding surface is the key to slope sliding. Sliding surface of loess landslide is mostly developed in the surface or inner of clay layer. Clay layer and upper layer are saturated and intenerated, making land change slowly. With the increasing distortion of slope body, sliding surface is formed gradually. Ground water has great role in declining shear-resistance intensity of sliding layer. Under the action of gravity and external forces, plasticity area is produced and developed, increasing the amount and rate of distortion. When the amount or rate of distortion exceeds allowable value, the slope body produces rheological damage along plasticity area, forming local sliding surface, which indicates that slope wriggling changes into the accelerating stage. Local sliding surface develops continuously, reaching the state of sliding preparation when perforating entirely.

The loess landslides are affected by topography, geomorphology, rainfall and earthquake, and frequently occurred in strips or sheets. The Loess landslides impose serious threats on human livelihood and property. Therefore, the study on mechanism and control measure of different types of loess landslide is an urgent task.

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